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LATERAL ASYMMETRY ENVELOPE EXPANSION TESTING ON A HIGHLY AUGMENTED FIGHTER/ATTACK AIRCRAFT

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I. Abstract

Modern fighter aircraft flight control systems are typically highly augmented to tailor flying qualities, increase departure resistance, and help protect the airframe structure throughout the flight envelope. To successfully defeat hardened targets, fighter/attack aircraft need to be capable of employing larger and heavier weapons than were envisioned when the aircraft was designed. The high lateral asymmetries that result from normal employment of these weapons represent a significant off-design condition that may have a severe impact on stability and control. Adequately defining flight envelope limits for these situations requires a flight test program that could result in a departure from controlled flight, loss of the aircraft, and possibly the aircrew. This paper presents the preliminary results of a flight test program conducted to expand the lateral asymmetry limits of the F/A-18. This flight test program addressed the stability and control, structural, and mission suitability issues associated with lateral weight asymmetries up to 28,000 ft-lb. In addition, test data was generated from which estimates of the maximum lateral store carriage asymmetry and its associated flight envelope could be made. Initial results indicate that with certain limitations, flying qualities are acceptable for performing typical mission tasks such as air-to-ground weapons delivery, in-flight refueling, and formation flight at asymmetries up to 28,000 ft-lb. Moreover, the test results indicate that the current flight manual maneuvering limitations could be expanded significantly within the existing 12 deg angle-of-attack limits. This paper will also address the flight test methods and real-time flight test tools proposed by the authors[1] for mitigating the risks associated with this type of flight test.

II. Background

Large precision guided munitions or "smart" weapons are intended to be released individually from a stand-off distance using only mild maneuvering; however, operational usage has shown that the delivery profiles can require significant maneuvering to establish the proper release conditions to maximize the weapon's effectiveness. Under these conditions, an individual release of a 2,000 lb class weapon, where physical size of the ordnance requires it to be carried on outboard pylons, will result in a lateral weight asymmetry well above the current F/A-18 flight manual limits. Currently, the fleet is required to use unique combinations of weapons and external fuel tanks on the wing stations to remain within the flight manual limits while retaining the capability to deliver individual ordnance to different targets. Although the F/A-18 can carry a considerable mix of weapons, a higher lateral asymmetry limit would increase the store carriage options available to fleet squadrons. Another consideration is the possibility of landing with such asymmetries when dealing with "hung-store" emergencies or when the expense of these large weapons dictates bringing back unexpended assets if the aircraft were capable of doing so. Also, expanding the limit would provide the F/A-18 with an established flight envelope such that the flight test burden would be reduced to affordable levels for future store certification programs.

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The objectives of the lateral asymmetry limit expansion program on the F/A-18 were: 1) determine if the control input restrictions for lateral asymmetries between 22,000 and 26,000 ft-lb could be relaxed, 2) to expand the aircraft's current 26,000 ft-lb limit to its maximum capability, 3) determine if vertical tail and pylon structural loads remain within acceptable limits throughout the required flight envelope, and 4) recommend suitable flight manual limits and wording for the flight characteristics section of the flight manual. However, due to budgetary constraints testing was performed to provide only a 28,000 ft-lb limit for the fleet instead of establishing the aircraft's maximum capability. This is the highest asymmetry foreseen with existing or soon-to-be certified stores.

III. Flight Test Issues

The test envelope and test maneuvers for this expansion program were defined by considering the operational use of large stores as described above, flight mechanics issues associated with lateral asymmetries, and F/A-18 flight control system specific characteristics. The later two subjects are described in the following sections.

Flight Mechanics Issues

Figure 1 illustrates several of the flight mechanics issues associated with asymmetric loadings. The most obvious issue is the lateral offset in the center of gravity (CG) from the aircraft's longitudinal axis. This introduces non-zero values for the products of inertia, I_{xy} and I_{yz}, since there is no longer a plane of symmetry. For example, a 2,300 lb store on the outboard station shifts the center of gravity as much as 10 inches from the F/A-18's centerline. In addition to the CG and inertia characteristics, consideration was given to the possible aerodynamic effects of the store asymmetry. However, wind tunnel data indicated these effects to be negligible when compared to the CG offset.[1]

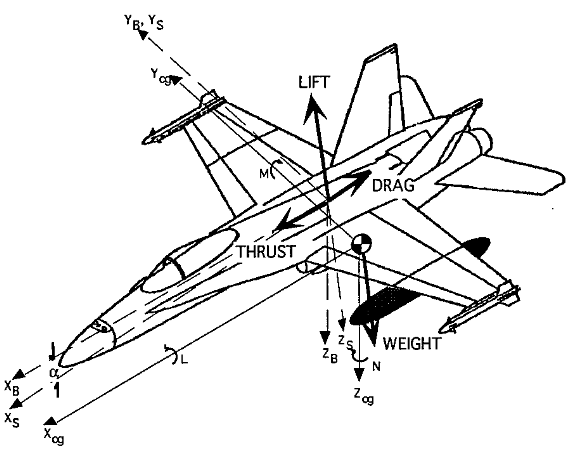

Figure 1
AXIS SYSTEM FOR AN AIRPLANE
WITH AN ASYMMETRIC LOADING

The presence of a large asymmetry creates large trim requirements to maintain balanced wings-level flight and because of the CG offset, pilot inputs in one axis result in unintended perturbations in the other two. For example, a pure longitudinal stick input results in undesirable roll moments which require lateral stick to counter. In aircraft with augmented flight controls like the F/A-18, the task may be further complicated by the requirement for additional compensation to counter the effects of flight control system (FCS) interconnects, such as those between the rolling surfaces and the rudder. These factors complicate the performance of the primary mission task of weapons delivery and other precision handling qualities tasks. The weapons delivery task is further complicated when, after dropping one store, the lateral center of gravity shifts instantaneously from the centerline. The result is an aircraft with flying qualities vastly different from the instant before in a loading which can be at the flight manual limit.

Test Aircraft Considerations

The F/A-18 FCS is an irreversible, full authority control augmentation system (CAS) consisting of two digital flight control computers (FCCs), each having two channels running in parallel to provide four channel redundancy for each control axis.[2] The control augmentation system uses gain scheduling, cross-axis interconnects (e.g., rolling surface to rudder) and closed-loop control of aircraft response to enhance flying qualities, protect the aircraft from overstress, actively control structural mode oscillations and augment basic airframe stability. The F/A-18 uses five left/right pairs of hydraulically actuated flight control surfaces: stabilators, rudders, ailerons, leading edge flaps, and trailing edge flaps. The mechanical surface deflections are shown in Table I; however, the control

Table I
MAXIMUM CONTROL SURFACE DEFLECTIONS

Control Surface	Maximum Surface Deflections
Stabilator	24 deg TEU to 10.5 deg TED
Aileron	25 deg TEU to 45 deg TED
Rudder	30 deg TEL to 30 deg TER
Trailing Edge Flap	8 deg TEU to 45 deg TED
Leading Edge Flap	3 deg LEU to 34 deg LED

Note: TEU = Trailing Edge Up TED = Trailing Edge Down
TEL = Trailing Edge Left TER = Trailing Edge Right
LEU = Leading Edge Up LED = Leading Edge Down

system mode logic and gain schedules can limit the surface deflections to less than the mechanical maximum depending on flight condition.

For example, in the lateral axis, control surface command authority across the flight envelope is scheduled as a function of Mach number, angle of

attack, normal acceleration, altitude, and airspeed. This is illustrated in figure 2 showing the scheduled command authority limits for maximum commanded differential stabilator deflection (i.e., full lateral stick input).

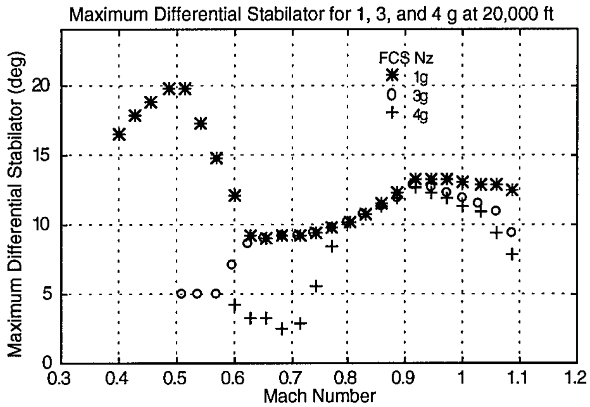

Figure 2
MAXIMUM DIFFERENTIAL STABILATOR WITH FULL LATERAL STICK INPUT

Figure 3 presents an estimate of the total rolling moment available as a function of Mach number for 1, 3, and 4 g at 20,000 ft and provides trend information

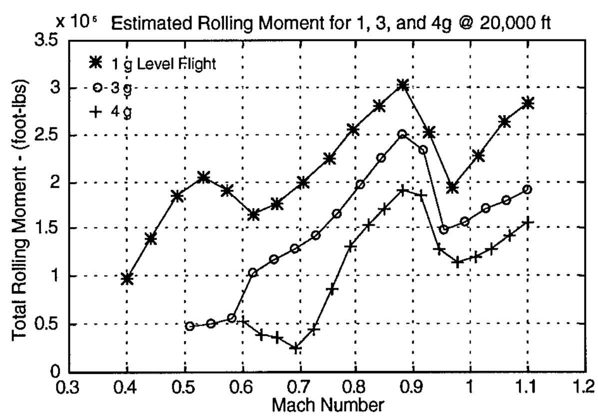

Figure 3
ESTIMATED ROLLING MOMENT WITH MAXIMUM LATERAL CONTROL SURFACE DEFLECTION

regarding the effects of FCS authority limiting on lateral control power across the maneuvering envelope.

It must be emphasized that the curves shown in figure 3 are valid only for a specific gross weight and center of gravity shown. A different weight would result in a different AOA and/or Nz, both of which are inputs to the roll control surface limit schedules. This complex relationship between the control authority and aircraft weight, which varies significantly during a sortie, suggests that the traditional display of lateral stick deflection alone may not be an accurate indicator of control margin for flight test monitoring purposes. A strategy for providing additional indications of control margin is discussed in the next section.

An additional factor owed to the modern, highly augmented control system is the influence of cross-axis interconnects on flying qualities and structural loads. Previous flight tests and man-in-the-loop simulation highlighted the impact of high lateral asymmetries on the indented design of the Rolling-Surface-to-Rudder Interconnect (RSRI): coordination of rolling maneuvers. During accelerated flight, the RSRI also responds to the rolling surface deflections required to counter the moment due to the weight asymmetry while maintaining bank angle. Simulation showed that the RSRI could introduce significant levels of sideslip (> 10 deg) with large asymmetries in accelerated flight, creating a potential departure scenario. At high dynamic pressures, large sideslips also increase the loads on the vertical tails.

One final note about the F/A-18 FCS is the presence of a roll rate limiter designed to limit the maximum roll rate to approximately 150 deg/sec when wing stores are present, thus keeping pylon loads within acceptable limits.[2]

IV. Test Execution

Test Loading and Asymmetry Build-up Sequence

Instead of using several different stores of various weights, it was preferable to maintain a constant aerodynamic configuration. Therfore, a method was devised for establishing asymmetric test loadings using fuel in an external fuel tank on one wing station to control lateral asymmetry. An example of the test loading is shown in figure 4.

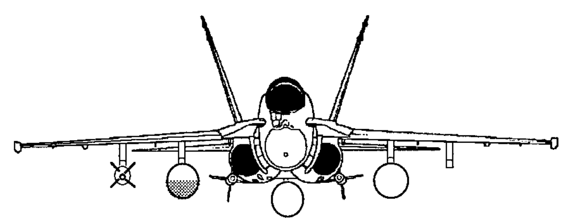

Figure 4
F/A-18 ASYMMETRIC TEST LOADING

However, this method was complicated by the F/A-18's fuel system in that there is no capability to transfer fuel from only one external wing tank; the pilot can only

control transfer of fuel from both tanks at the same time. To overcome this limitation in the production fuel system, the external wing tank adjacent to the store loaded on the right wing was isolated from the aircraft's fuel system by blocking off the pressure and fuel feed lines at the pylon interface. The isolated tank was then fueled with the exact amount required to establish each test lateral asymmetry. Transfer of fuel from the other external wing tank was retained to allow the pilot to takeoff with a lateral asymmetry that would remain well within the normal flight manual limits until reaching a safe test altitude.

Using a fuel tank to control lateral asymmetry had an interesting side benefit that allowed a little gamesmanship to be used to increase flight test efficiency. Ordinarily, when tests are completed at a given level of asymmetry, a return and landing would have been required to reload the aircraft to a symmetric loading before performing the transient test points. Then another return and landing would have been required to reload yet again to establish the next level of lateral asymmetry. However, the test team devised a means by which fuel in the transferable external tank could be used to set-up the next level of asymmetry after performing the asymmetry transient test and proceed with testing. Instead of returning to load the aircraft symmetrically for the short flight to evaluate the asymmetry transient and then return again for the next asymmetric loading, only one return and landing was required. Figure 5 illustrates the progression of build-up in lateral asymmetry.

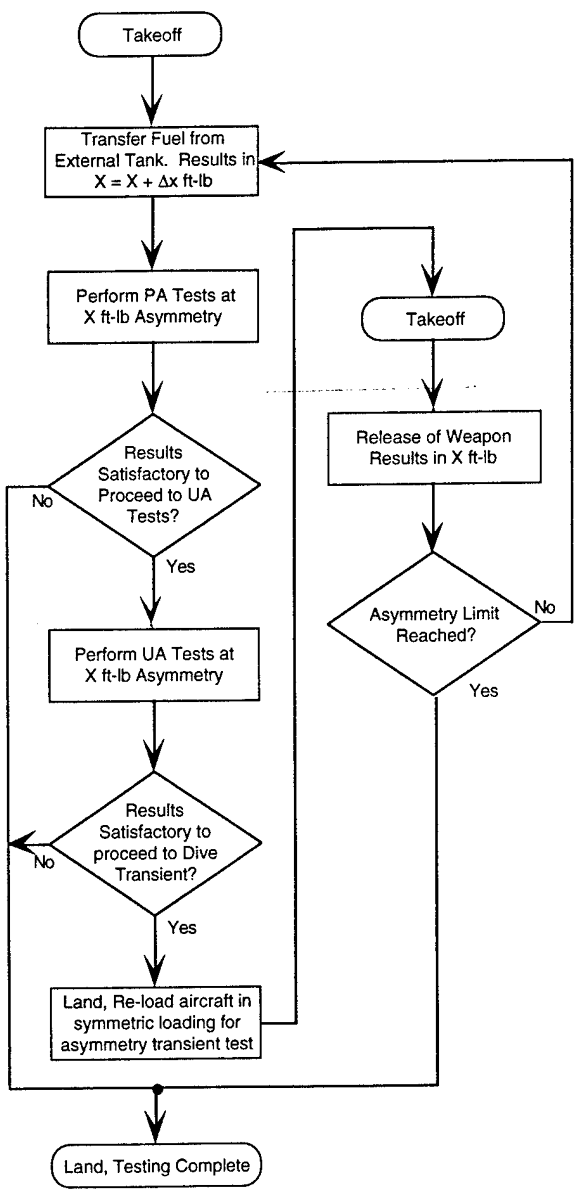

Figure 5
BUILDUP PROGRESSION

Test Maneuvers

Integrated test blocks were devised for execution at multiple flight conditions and with various aircraft configurations to address the issues outlined in section II. To satisfy the objective of performing safe landings with high asymmetries during flight test and to support an eventual fleet clearance for routine field based operations (as opposed to carrier based), tests were performed in the Power Approach (PA) configuration at 5,000 ft. To mitigate the flight test risk of having to make an approach and landing early in a flight, the PA test matrix was performed first and then repeated with one engine at idle to simulate single-engine operations in the landing configuration (PA-SSE). To satisfy the weapons delivery objective, test maneuvers were performed in the Gear-Up, Flaps-Auto (UA) configuration at 30,000, 40,000, and 15,000 ft, respectively. The maneuvers included:

a. Pitch and yaw doublets performed to familiarize the pilot with differences from one test point to the next and to collect data on the free response of the aircraft for stability analysis (PA and UA).

b. Wings-Level Sideslips (WLSS) to replicate as closely as possible the crosswind landing technique in the F/A-18 (PA only).

c. Bank-to-Bank rolls to evaluate lateral control power and the possibility of eliminating the half lateral stick limits (PA and UA). Bank-to-Bank rolls were also performed at elevated load factors to evaluate the effects of the RSRI and determine if any flight manual limits on lateral maneuvering at elevated load factors would be required (UA only).

d. Normal two engine and simulated single-engine waveoffs (W/O) from a simulated landing approach at altitude (PA only).

e. Handling Qualities During Tracking (HQDT) during parade formation to investigate Pilot Induced Oscillation (PIO) susceptibility (PA only).

f. Wind-Up Turns (WUTs) to evaluate lateral stick required to counter the asymmetry at elevated load factors, first away from the heavy wing

and then into the heavy wing. WUTs were performed into the heavy wing first so that if the limits of lateral control power were reached, the airplane would roll upright towards wings level.

After all the basic build-up maneuvers were performed, a series of dive delivery profiles were flown at commonly used dive angles with a simulated release at progressively lower altitudes followed by a pull to 4g. This was to demonstrate that sufficient lateral control power remained for recovering to level flight. Finally, bombs were released from symmetric loadings to evaluate the effects of instantaneous changes from a symmetric loading to the maximum asymmetry allowed by the proposed flight manual limit.

Maneuver Termination Criteria

The maneuver termination criteria applied to this program were derived from current F/A-18 flight manual limitations, experience with previous asymmetric loading tests, and results from fixed-base piloted simulation. Simulation was used to estimate maneuvering requirements to perform typical mission tasks, as well as to target the maximum asymmetry and allowable AOA and sideslip excursions.

Among these factors was data from early F/A-18 lateral asymmetry testing that indicated departures from controlled flight would rapidly transistion into a fully developed spin with marginal recovery characteristics. Consequently, in the early planning phases of these tests emphasis was placed on departure avoidance!

The flight manual AOA limits were retained for these tests. Previous flight test experience and wind tunnel data, as well as the aforementioned simulation effort showed that the 12 deg AOA limit provided acceptable maneuvering capability and an adequate margin with respect to departure resistance.

For the F/A-18 there are no sideslip limits published in the flight manual and the only cockpit indication of sideslip is a yaw string on the nose barrel. In an aircraft configured with an asymmetric store, trimming to center the slip indicator ball will result in a small sideslip at the trimmed condition. These factors combined with the influence of the asymmetric loading on cross axis and inertial coupling and the capability of the RSRI to introduce significant levels of sideslip during maneuvering flight led the test team to establish sideslip limits of 7 deg in subsonic flight and 5 deg for supersonic flight.

Real Time Tools

Recent Department of Defense policy has increased the emphasis on the use of modeling and simulation for increasing the efficiency of testing. It was recognized early in the development of this test program that better information could be presented to the test conductor if the capabilities of the F/A-18 simulation were merged with onboard aircraft sensor data. A control margin prediction tool or display could then be made available in real-time to assist the test conductor in safety monitoring. This concept of merging real-time simulation output with real-time telemetry (TM) is not new (e.g. NASA's X-29 real time calculation of phase and gain margin during envelope expansion[3,4]); however, it has not been extensively applied. A prototype network-based link at NAWCAD Patuxent River between the telemetry system and the real-time simulation facility was developed and demonstrated for this program. An overview of the TM-simulation display configuration for this program is given in Figure 6 and described below.

Two desirable pieces of information from the simulation were the maximum allowable differential surface deflections for the experienced flight conditions and the rolling moment associated with these deflections. Although the scheduled surface authority limits are not available on the MIL-STD-1553 multiplex databus, all flight control computer sensor inputs are and were available on the TM data stream. They were used to drive a FORTRAN simulation of the lateral axis control system to calculate the maximum surface deflections attainable. Supplementing these with the TM flight condition and fuel loading allowed an aerodynamics model to predict the maximum available rolling moment.

Control and moment authority data was then displayed to the test team in a manner that was easily interpreted in a real-time situation. The display allowed the team to monitor for potential surface deflection saturation and to insure that some margin of lateral control power was maintained during accelerated flight. The pertinent parameters were the difference between the amount of control surface deflection/moment commanded by the pilot and the maximum available from the FCS. However, the magnitude of these parameters change significantly throughout the flight envelope, so ratios of commanded to maximum available rolling surface and moment were envisioned as useful supplements to the $^2/_3$ lateral stick test limit used in past programs, especially during accelerated flight maneuvers such as wind-up turns or steady pulls where the pilot is controlling bank angle.

The two ratios of interest were the percentages of rolling surface and rolling moment used as shown in equations (1) and (2).

In equation (1), the numerator terms were the telemetered surface positions and denominator terms were the output of the simulation. The numerator term in equation (2) is the rolling moment caused by the asymmetric loading multiplied by the filtered signal from the normal accelerometer. The resulting product

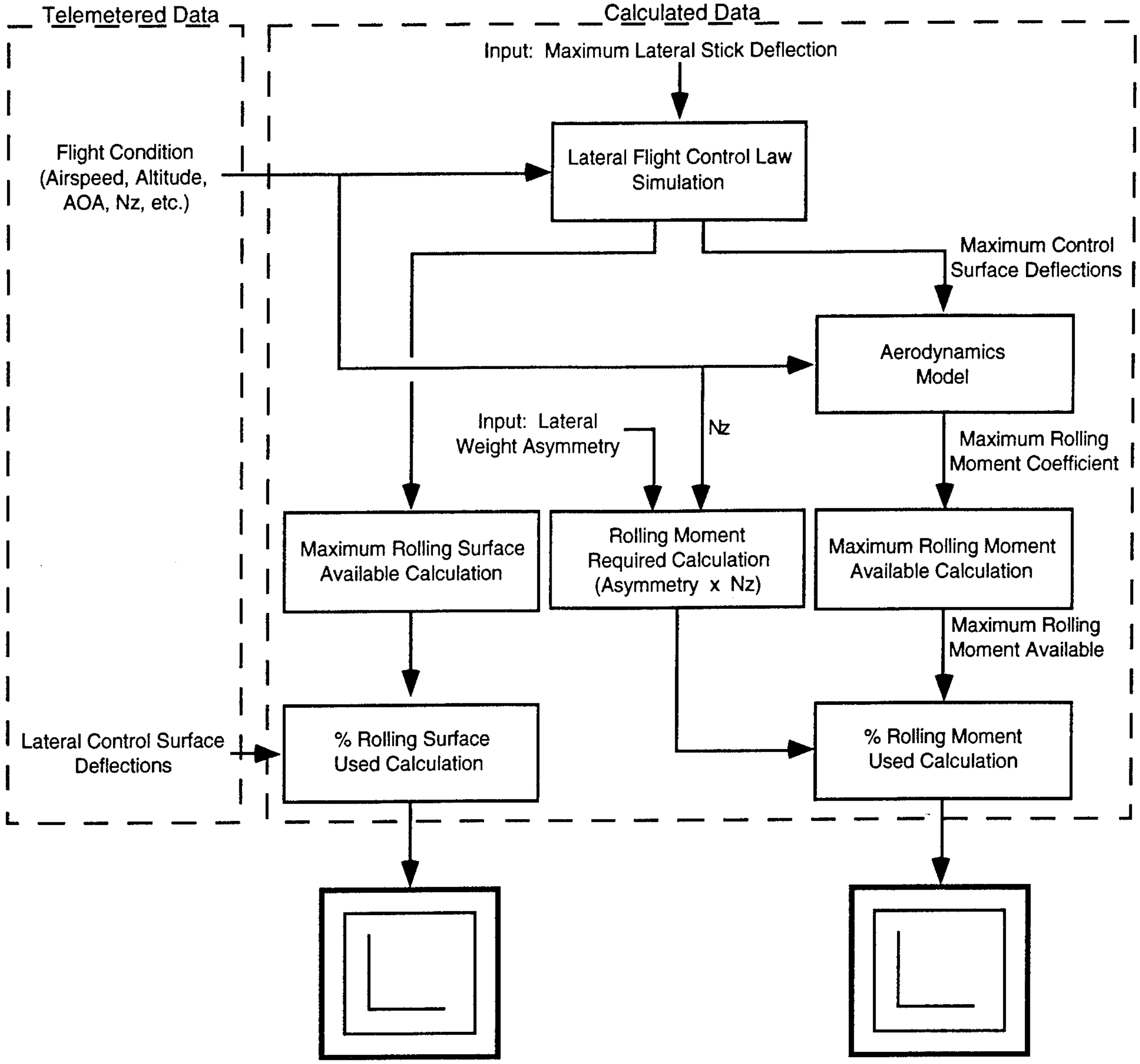

Figure 6
OVERVIEW OF REAL-TIME DISPLAYS

$$\%\ \text{Rolling Surface}\Big|_{\text{used}} = \frac{\delta_{\text{aileron}} + \delta_{\text{diff stab}} + \delta_{\text{diff lef}} + \delta_{\text{tef}}}{\delta_{\text{max aileron}} + \delta_{\text{max diff stab}} + \delta_{\text{max diff lef}} + \delta_{\text{max tef}}} * 100 \qquad (1)$$

$$\%\ \text{Rolling Moment}\Big|_{\text{used}} = \frac{\text{Weight Asymmetry} * \text{Load Factor}}{\text{Rolling Moment}\Big|_{\text{max available}}} * 100 \qquad (2)$$

represents the roll power that the rolling surfaces must generate to maintain roll control. The denominator is the maximum available rolling moment calculated by sending the maximum surface deflections through the aerodynamic model, which calculates the non-dimensional rolling moment coefficient based on surface deflection and flight condition (i.e., AOA, AOSS, and Mach number). The maximum rolling moment is then calculated by multiplying the coefficients by dynamic pressure and the reference length.

Figure 7 illustrates the real-time display associated with equation (1). The shaded area on the grid represents the criteria of 0.75 (75%) which was set as a "knock-it-off" boundary for Roll Control Authority Ratio and the $^2/_3$ lateral stick deflection criteria used in past F/A-18 programs. The "+" represents the current state while the line (or "tail") represents the last several seconds of data, allowing the test team to observe data trends. It should be noted that the hypothetical case shown below

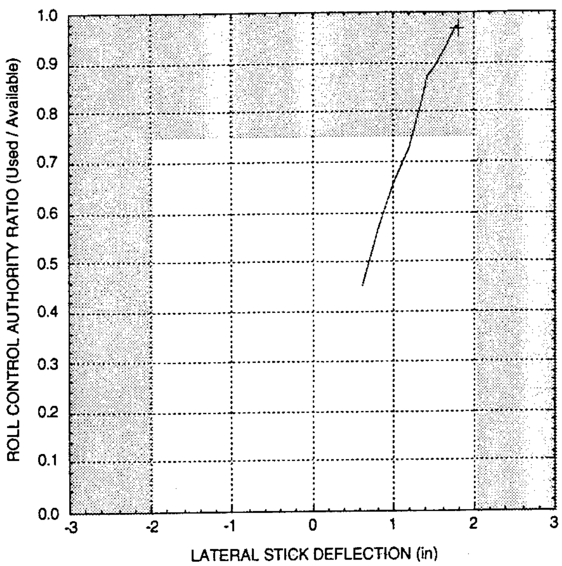

Figure 7
REAL-TIME DISPLAY OF ROLL CONTROL AUTHORITY RATIO

illustrates a condition where the $^2/_3$ lateral stick criteria does not ensure adequate margin. The real-time display associated with equation (2) is analogous to that of equation (1).

The real-time tools created specifically for this program integrated several sources of information into one display allowing the test conductor to maintain a level of situational awareness never before experienced. These tools were routinely used as the first source of more timely "knock-it-off" calls to the pilot. For example, using the display shown in figure 7 during wind-up-turns, "knock-it-off" calls were made to the pilot as the cursor crossed either the 75% rolling surface used boundary or the $^2/_3$ lateral stick boundary. Each time this call was made, the pilot concurred that the call came right as he was noticing a reduction in lateral control power; i.e. while concentrating on task performance, he may have pressed further, had the call from the ground station not come when it did. This is not to say that the pilot would have continued into an unsafe condition but rather that calls from the ground station occurred at just the right time to prompt the pilot to effect recovery to 1 g level flight and ensure control margin limits weren't exceeded. The test team is highly confident that these real-time tools added to the safety of the test by reducing the risk of encountering an out-of-control situation and should be considered for future efforts in this unique and high risk type of flight test.

In addition to providing display information, real-time simulation played a part in reducing the post-flight data reduction. The flight control law simulation was exercised to replicate the RSRI command which was not available on the databus for TM. Replicating the RSRI in real-time, as opposed to post-flight in off-line simulations with recorded data, provided the test team with a complete package of data at the conclusion of each test flight. This allowed for a more rapid examination of the data between successive flights. The replicated RSRI command was also available for display in real-time using the standard test engineer station monitors.

V. Results

General

Initial results indicated that with certain limitations, the flying qualities were clearly adequate for typical mission tasks such as air-to-ground weapons delivery, in-flight refueling, and formation flight at asymmetries up to 28,000 ft-lb. Moreover, the test results indicated that the current flight manual maneuvering limitations could be expanded significantly within the existing 12 deg AOA limit. Finally, pilot opinion indicated that the flying qualities observed in flight agreed well with what they saw during pre-flight simulation training periods.

Gear Up Configuration

1g Level Flight

Across the Mach/altitude range tested, lateral surface deflections required to trim wings level with zero roll rate resulted in rudder inputs via the RSRI. With a heavy right wing, RSRI inputs generated aircraft nose left sideslip and were greater than those required to "center the ball" (i.e., over coordinating rudder inputs). Consequently, the pilot was required to use right rudder pedal to reduce the sideslip while retrimming to ball centered, coordinated flight. At the trimmed conditions for asymmetries out to 28,000 ft-lb the resulting sideslip angles were typically less than 2 deg aircraft nose left.

In general, flying qualities in configuration UA were considerably better above 250 KCAS than below. Although the pitch-roll coupling characteristics were consistent across the airspeed range tested, at low airspeeds and AOAs approaching 10 deg, pitch doublets

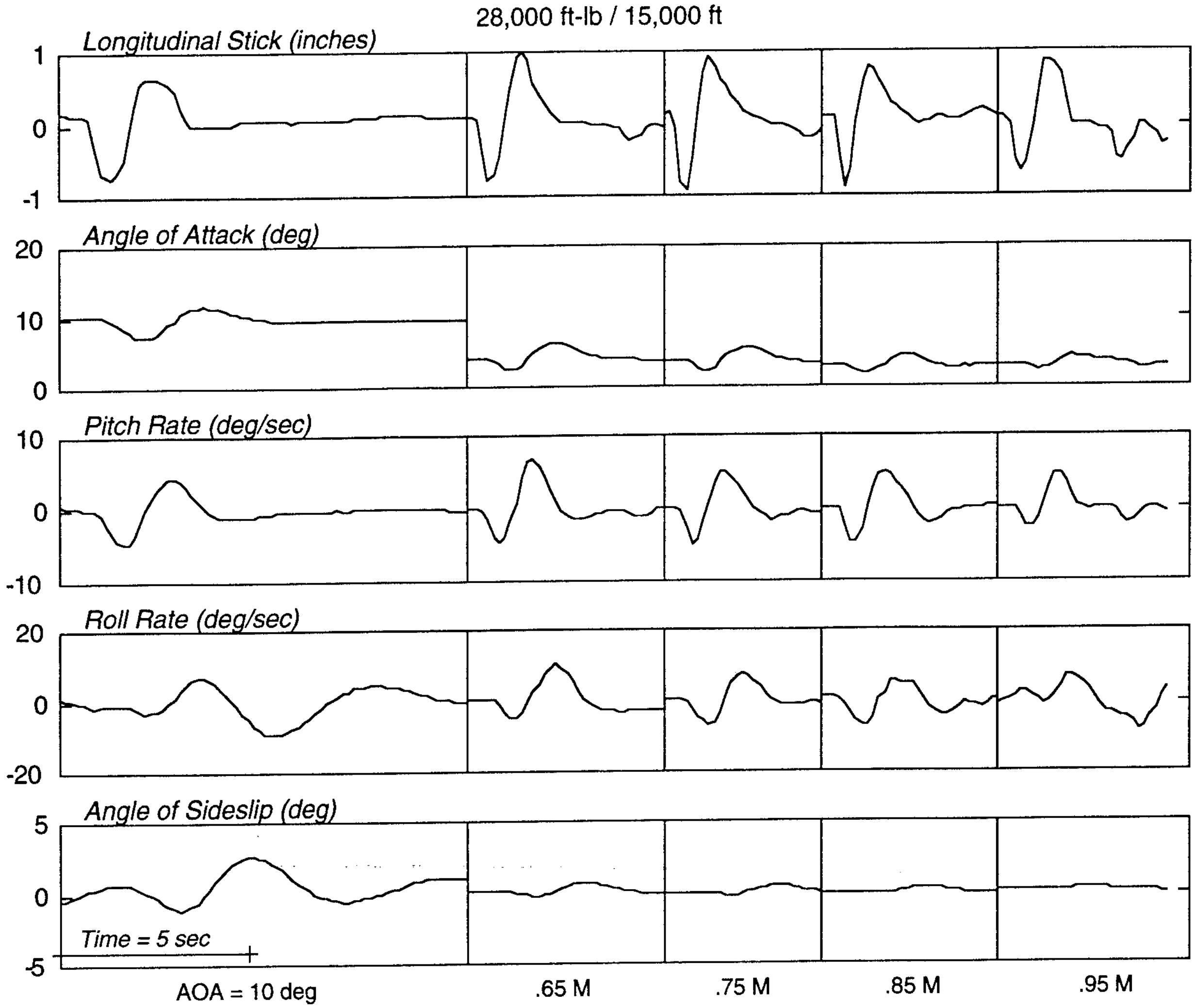

Figure 8
AIRCRAFT RESPONSE TO PITCH DOUBLETS AT VARIOUS MACH NUMBERS

resulted in lightly damped roll rate and sideslip oscillations as shown in figure 8.

Above 250 KCAS, roll rate and sideslip oscillations were well damped. Rudder pedal doublets resulted in the same, lightly damped, roll rate and sideslip oscillations at low speeds; however, there was very little coupling into the pitch axis. Pilots commented that the airplane felt "loose" in the directional axis and controlling AOA during rolling maneuvers was somewhat difficult. Airframe buffet and vortex rumble were observed as AOA approached 12 deg; however, pilot comments indicated that there was little to no warning when the 12 deg AOA limit was reached. In the lateral axis, Cooper-Harper handling qualities ratings (HQR) below 250 KCAS and up to 10 deg AOA for 30-to-30 and 45-to-45 deg bank angle captures with half lateral stick inputs were level-1; whereas, full lateral stick inputs sometimes resulted in high level-2 ratings. Above 250 KCAS, half and full lateral stick 60-to-60 deg bank angle captures indicated solid level-1 flying qualities. Overall, the flying qualities in 1 g level flight were considered good; however, the low speed end of the envelope was defined by the pilot's comfort level based on his perception of controllability during closed loop tasks.

Accelerated Flight

In the test planning phases there was concern that during accelerated flight, full lateral stick inputs into the heavy wing may defeat the roll rate limiting function in the FCS and exceed 150 deg/sec which could result in unacceptable structural loads. To address this concern, half stick inputs were used as a build-up to full stick inputs. However, preliminary analysis showed that roll rates were below 150 de/sec and pylon post rolling moment and hook loads remained well within limits.

Preliminary analysis indicated that at Mach numbers of 0.75M and above, ±60 deg bank-to-bank captures at 10 deg AOA (i.e., accelerated flight) generally resulted in solid level-1 ratings. At 0.65 Mach, HQRs were

grouped between low level-1 and high level-2, with rolls away from the heavy wing generating the lower ratings. This was partially due to the small amounts of aircraft nose left sideslip at the target AOA/Mach test conditions that kinematically coupled into AOA when rolling away from the asymmetric store.

Wind-up turns to 12 deg AOA required substantial left lateral stick inputs to counter the rolling moment induced by the effects of accelerated flight on the right wing heavy asymmetry. The corresponding lateral surface deflections generated rudder inputs via the RSRI which in turn tended to increase the aircraft nose left sideslip as shown in figure 9. Sideslip excursions during wind-up turns were typically less than 3 deg. Pilots commented that flying qualities during the wind-up turns were smooth and predictable and not surprisingly, the large lateral stick requirements to maintain bank angle were the main limitation in maximum controllable load factor. What was surprising, however, was that lateral stick travel was limited during WUTs to approximately $^2/_3$ full travel by the pilot's inflated G-suit. This condition was verified on the ground by manually commanding inflation of the G-suit while deflecting the control stick laterally. This human factors limitation on control power was not foreseen and should be considered in any program where rolling at high load factors is required. This is a perfect example of how the focus of testing needs to be as broad as possible to consider not only the aircraft and its control system, but even the effects of all "possible" interfaces between seemingly unrelated systems like the pilot's flight gear for potential impact on test results. Fortunately, this oversight had minimal impact on the safety of this test.

Weapon Delivery profiles

The ultimate objective of this test program was to provide an asymmetric limit that is safe and usable for fleet operations. Build-up maneuvers established that control power should be sufficient at the load factors typically used to recover from a high angle dive bombing delivery but the suitability of the aircraft for actually delivering ordnance during this type of maneuver at 28,000 ft-lb remained to be demonstrated. First, a series of dive delivery profiles were flown at commonly used dive angles with a simulated release at progressively lower altitudes followed by a pull to 4g recovery. The roll-in was typically completed by rolling away from the heavy wing. Capturing the inverted flight bank angle during the roll-in was easy, requiring one small lateral stick input to stop the roll. Pitch rates during the high altitude roll-ins were slightly less than desired at the 12 deg AOA limit but capturing the desired dive angle was easy, requiring the pilot to relax aft longitudinal stick pressure as the desired dive angle was approached. Small pitch attitude adjustments resulted in small bank angle excursions and increased lateral stick activity which, although annoying, would

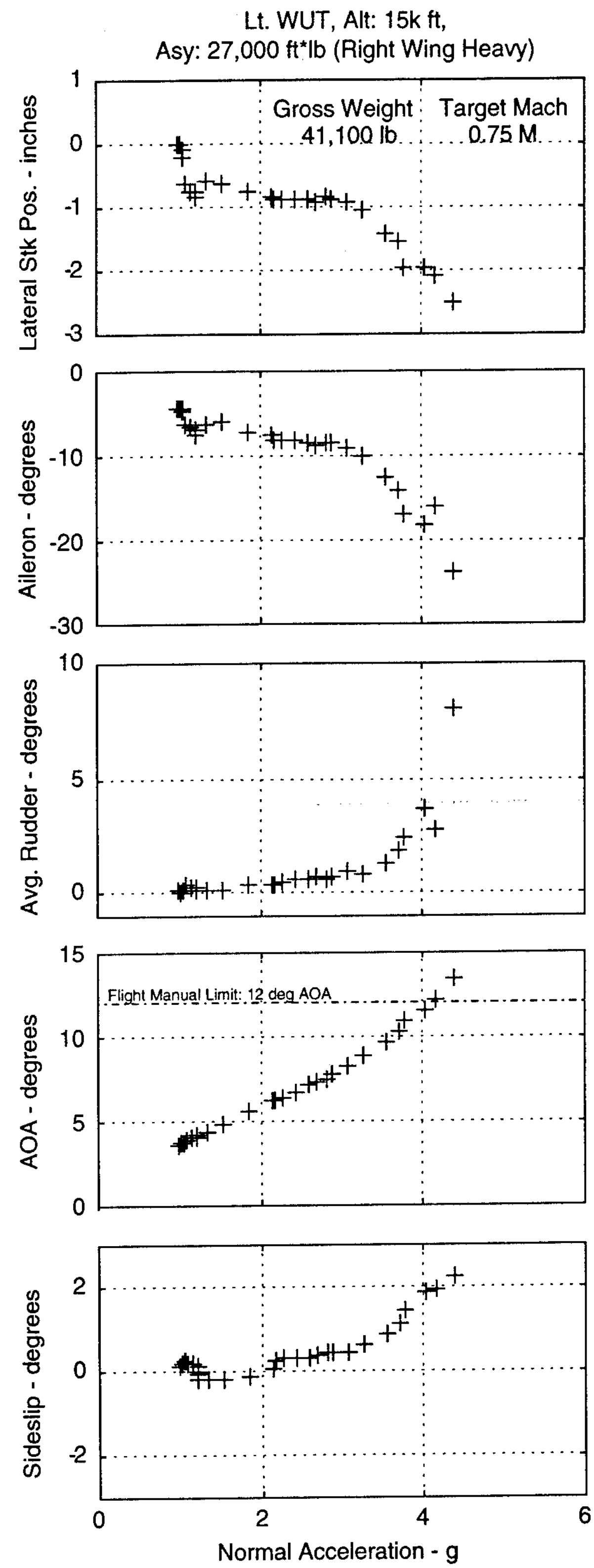

Figure 9
WIND UP TURN AT 0.75 MACH

not prohibit the pilot from capturing the proper weapon delivery parameters. Small corrections to the dive angle were more difficult, requiring coordinated lateral stick inputs to counter the small, uncommanded bank angle changes which occurred with longitudinal stick inputs. Approximately 2/3 left lateral stick (2 in) was required to maintain wings level during dive recoveries, which was uncomfortable and resulted in more cautious longitudinal control inputs. This resulted in a slower g-onset rate during the recovery which, in turn, resulted in 25-30 percent higher altitude loss than expected. The increased altitude loss during dive recovery with asymmetric loadings must be included in the pilot's planning of weapon delivery profiles.

There was some concern over the effects of asymmetry transients that would be experienced when commencing the first attack with a symmetric loading, releasing one weapon and then maneuvering to begin another attack, (i.e. instantaneous changes from zero lateral asymmetry to 28,000 ft-lb). As the final test point at each asymmetry tested, an additional weapon delivery profile was conducted starting with a near symmetric loading and then releasing one store to evaluate the transient effects. Pilots commented on a small perturbation in roll towards the heavy wing as the weapon was released but it was easily controlled.

Approach and Landing Configurations

Flying qualities were evaluated with half and full flaps at both 8.1 deg (normal approach "on-speed" AOA) and 10 deg AOA. Additionally, simulated single engine flying qualities were evaluated with half flaps at 8.1 deg AOA. Aircraft response to pitch doublets was sluggish, but approximated response characteristics of a symmetrically loaded aircraft. Response to rudder pedal doublets was asymmetric and categorically larger for the left pedal inputs. The difference in apparent rudder effectiveness was also noticeable during the wings level sideslips, where the airplane was easily driven to the sideslip test limit of 7 deg aircraft nose left with 1/2 to 2/3 left pedal inputs. Whereas, full right pedal only generated 5 to 6 deg of sideslip. Bank-to-bank captures of ±30 and ±45 deg with half lateral stick inputs were easily controlled, generating Level-1 HQRs. These maneuvers resulted in some coupling which increased AOA for left rolls, and decreased in AOA for right rolls. In general, full stick deflection was too much for the task, and generally resulted in degraded HQRs (low level-1 to high level-2).

With 28,000 ft-lb of lateral asymmetry, formation at "on-speed" angles of attack was not significantly more difficult than without the lateral asymmetry. There was generally no noted difference between flying on the right or left side of the lead aircraft. Turns into the wingman, which required the test aircraft to reduce speed (increase angle of attack) to stay in position were much more uncomfortable and more difficult to fly than turns away from the wingman, which required the test aircraft to accelerate to maintain position. On a related subject, position keeping while flying at 10 deg versus 8.1 deg angle of attack was much more difficult and uncomfortable. There were a number of occasions where position keeping within tight tolerances required the test aircraft to slow to 12 deg angle of attack; this required the test aircraft to sacrifice maintaining a good position in favor of good angle of attack control. Simulated single engine position keeping was notably more difficult than with two engines, due mainly to the large throttle commands required to effect fore and aft relative position, and the rudder and lateral axis trim changes that accompanied them.

In spite of the difficulties discussed with formation flight, pilot comments generally indicated that the overall handling qualities at the normal approach AOA of 8.1 deg with asymmetries up to 28,000 ft-lb were quite good in the landing configuration with flaps half or full. Recommendations for flight manual changes will probably include the use of a straight-in landing approach as the preferred method and if a landing approach must be made in formation, half flaps will be recommended for improved handling qualities.

Critical Engine

Question: All else aside, which is the critical engine when large lateral asymmetries are present? The fact that this question is being asked should tip off the reader that the answer isn't obvious, at least in the case of the F/A-18. Here again the RSRI feature in the F/A-18 flight control laws complicates the issue. As mentioned previously, anytime asymmetries are present, it was expected that the RSRI would have a slight detrimental effect on UA flying qualities, particularly at higher load factors. What was not readily apparent until this flight test program was how strongly the RSRI can effect single engine flying qualities. For example, with a large store on the right wing resulting in an asymmetry in the range of 20,000 - 26,000 ft-lb, which engine is the critical engine? Without fail, every pilot and engineer polled analyzed the problem this way:

> "A large weight asymmetry on the right would tend to yaw the aircraft to the right resulting in sideslip from the left because of the drag asymmetry. So the worst case would be with the right engine out because the left engine will also tend to yaw the aircraft to the right. Right?"

For most airplanes, this would be true but, with an RSRI in the control laws, the F/A-18 FCS response is remarkably different. Hindsight always has perfect vision but everyone expected (assumed) that the asymmetric thrust effect would be more powerful and an engine out on the heavy side would be worst case. However, with both engines operating and trimmed in 1-g level flight, the rolling surfaces are deflected as

required to counter the weight on the heavy wing and maintain bank angle. In the above example, the RSRI responds to the deflected roll control surfaces by deflecting the rudders to the left to coordinate "a roll command". However, there is no roll and the result is an uncoordinated airplane with sideslip from the right instead of from the left as everyone expected. With the right engine at Idle, the right yawing moment from the thrust asymmetry tended to reduce the left yaw effect of the RSRI, requiring 30 lb of right rudder pedal force to coordinate the aircraft. But with the left engine at Idle, the pilot had to use 75 lb of right rudder pedal force to counter the RSRI command and keep the aircraft coordinated! The probable course of action in "the fleet" should an engine failure occur, would be to jettison store(s) as necessary to get rid of the asymmetry before landing. However, the flight manual only says "consideration should be given" to doing so and there may be reasons to still consider bringing back the store, if possible. This being the case, the flight manual should provide guidance to the pilot for making the decision.

Flight Envelope Verification

Initial results and pilot opinions indicate that with certain limitations, flying qualities are satisfactory during typical mission tasks (air-to-air, air-to-ground, in-flight refueling, formation flight, etc.) at asymmetries up to 28,000 ft-lb. However, for very sound safety reasons, only two pilots were allowed to fly the envelope expansion test points so they would be intimately familiar with the previous build-up trends. While enhancing test safety, this may have compromised their viewpoint of the average fleet aviator's ability to deal with the increased lateral asymmetry limit. It is highly likely that fleet aviators will not have much experience with large lateral asymmetries and their first experience may occur during the heat of battle or in an emergency situation such as a "hung" store. Therefore, the test team determined that there was a need for additional trained test pilots who had not previously flown in the program to fly at least one flight within the limits of the proposed flight manual changes as a "sanity check" before releasing the new limits to the fleet. Although this is not a common practice, it has been used in similar high risk programs that used a small pool of pilots for the expansion of limits and can do nothing but improve the confidence in these extreme "edge of the envelope" limits given to the fleet.

VI. Summary

Overall flying qualities of the F/A-18 are excellent with asymmetries up to 28,000 ft-lb and preliminary analysis indicates that the maximum capability of the aircraft is significantly higher. The 12 deg AOA limit provide acceptable maneuvering capability for executing normal air-to-ground weapons delivery tasks. Although the focus was on the effects of the augmented flight control system on roll control surface authority and rolling moment capability, the limiting factor actually had less to due with the augmentation but rather the interference between lateral control stick deflections and the pilot's G-suit at elevated load factors. Pilot qualitative comments indicate that the simulation agreed well with the flying qualities observed in flight.

What was not readily apparent until this flight test program was how strongly the RSRI feature in the FCS can effect single engine flying qualities. Simulated single engine testing revealed that the RSRI actually defines the critical engine for flying qualities to be opposite the "intuitive" conclusions arrived at by observing only the aerodynamic configuration. Results indicate that for the F/A-18, a failed engine on the side opposite the heavy wing is the critical case for flying qualities.

The real-time tools created specifically for this program integrated several sources of information into one display allowing the test conductor to maintain a level of situational awareness never before experienced. These tools were routinely used as the first source of more timely "knock-it-off" calls to the pilot and added significantly to the safety of the test by reducing the risk of encountering an out-of-control situation. These tools should be considered for future flight test work in this unique and potentially high risk type of experimental flight test. Finally, the real-time tools developed for this program fit well with DoD policy regarding increased test efficiency via modeling and simulation.

Future plans include performing a "verification" of the proposed flight manual changes to ensure that limited pilot participation in the envelope expansion phase of the program did not result in compromised viewpoints on the fleet aviator's ability to cope with the increased limits.

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[1] Dungan, G. D. and Clark, C. M., *Flight Testing Large Lateral Asymmetries on Highly Augmented Fighter/Attack Aircraft*, Proceedings of the 25th Annual Symposium of the Society of Flight Test Engineers, 1994.

[2] Krone, S. K., Arnold, L. D., and Hess, R. K., *F/A-18A/B/C/D Flight Control System Design Report, Volume I*, MDC 7813, Vol. I (Rev C), McDonnell Douglas Aerospace Company, St. Louis, 23 December 1992

[3] Hicks, J. W. and Petersen, K. L., *Real-Time Flight Test Analysis and Display Techniques for the X-29A Aircraft*, AGARD 73rd Flight Test Techniques Symposium Flight Mechanics Panel, 1988.

[4] Gera, J. and Bosworth, J. T., *Dynamic Stability and Handling Qualities Tests on a Highly Augmented, Statically Unstable Airplane*, 18th Annual Symposium of the Society of Flight Test Engineers, 1987.